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Research paper

A Four Novel Energy Pattern Factor Method for Computation of Weibull Parameter in Impact Strength Reliability of Fibre-Reinforced Concrete

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Abstract

Impact strength data is a noteworthy factor for designing airport pavements, civilian and military structures etc and it is ought to be modelled precisely. In order to achieve an appropriate modelling data, it is important to select a suitable estimation method. One such commonly used statistical tool is the two parameter Weibull distribution for modelling impact failure strength accurately besides the variations in test results. This study statistically commandsthe variations in the impact failure strength (number of blows to induce failure) of fibre reinforced concrete (FRC) subjected to drop hammer test. Subsequently, a four-different novel method for the computation of Weibull parameter (Shape parameter) based on the earlier researchers test results has been proposed. The accuracy of the proposed four novel method is demonstrated by comparing with power density method and verified with goodness of fit test. Finally, the impact failure strength of FRC is offered in terms of reliability. The proposed four NEPFM is very suitable and efficient to compute the shape parameter in impact failure strength applications.

1. Introduction

Concrete is a predominant building material in construction industry that possess relatively high compressive strength, but much lower tensile strength [1]. The brittle nature of concrete is generally counteracted by incorporation of fibres that significantly improve the impact strength and energy dissipation capacity of concrete [2-14]. ACI Committee 544 [15] published a report titled “Measurement of Properties of Fibre Reinforced Concrete” (ACI Committee 544, 1989),and it has provided seven methods for measuring the impact resistance of FRC, which include pendulum impact, drop-hammer, projectile impact and split-hopkinson bar test. Also, the report includes some standard test setup for specific testing types. ACI Committee 544 suggested that the impact strength value can be calculated by measuring the number of blows to induce first crack and failure.

A substantial research has been completed on impact response of FRC; majority of the researches have dealt with effect of fibres on concrete [16-21].Nataraja et al., (1999) studied the variations in impact strength of steel FRC explored using drop weight test. In case of FRC the coefficient of variation observed was 57 and 46% for first crack and failure respectively and the corresponding values were 54% and 51% for plain concrete. It was observed from goodness of fit test that the fitness was poor in case of both FRC as well as plain concrete for the impact test results produced from a normal distribution at 95% level of confidence. Based on this observed level of variation, minimum number of test could be suggested to reliably measure the material properties.

Song et al., (2005) (a) performed an extensive statistical analysis on scattered impact strength test results of high strength concrete (HSC) and high strength steel FRC subjected to drop weight test. Additionally, two regression equations were proposed to evaluate the number of blows induces failure from number of blows induces first crack. Moreover, the Kolmogorov–Smirnov test was performed on these two concrete and the results demonstrated that the HSC had roughly normally distributed first crack strength and failure strength while high-strength steel FRC had insufficient normally distributed first crack strength and failure strength. Also results indicated that the impact resistance of high strength steel FRC was higher compared to HSC. The first-crack strength and failure strength of high strength steel FRC was about 3.9 and 4.2 times that of HSC.

Song et al., (2005) (b) statistically commended the first crack strength, failure strength and strength reliability of Steel–Polypropylene Hybrid FRC (SPHFRC) and Steel Fibre Reinforced Concrete (SFRC). The results showed that the SPHFRC had the higher impact strength over the SFRC. The number of blows induce to first crack in SPHFRC and SFRC was 247 and 234 respectively, with a coefficient of variation of 54% and 59%. Similarly, the number of blows induce to failure in SPHFRC and SFRC was 356 and 330 respectively, with a coefficient of variation of 41% and 52%. The SPHFRC under repeated impact loads possessed slightly superior reliability over the SFRC. The Kaplan–Meier analysis indicated that first crack and failure strengths reliabilities were improved in SPHFRC when compared to SFRC.

Badr et al., (2006) examined the variations in drop weight impact test results of polypropylene, carbon and steel FRCby statistical approach. It was observed that the test results had large variations and in order to ensure an error of less than 10% it was necessary to increase the number of specimens at least to 40 per mixture.

Also, it was identified that this drop weight test was not reliable and it needs some modification which will increase its accuracy and reduce the large variation in test results.
However, a large scatter in the drop hammer test results were observed [22-28] owing to various factors, (i) inappropriate identification of first crack and failure by visual means[26] (ii) the free fall height of hammer that is tough to control, as the test is carried out manually[3] (iii) the point of impact that decides the impact resistance of concrete which might happen to be either on coarse aggregate or mortar region[13]. To counteract the scatter in impact test data and assess the effect of fibres in concrete, different statistical methods has been proposed by various researchers [22-28]. Two parameter Weibull distribution, which has newly been used broadly for the determination of impact and fatigue behaviour of FRC structures [4, 13, 26, 28-31].In order to overcome the problem stated above, the following investigation has been carried out in this research. However, from the literature review it was found that none of the researchers describes the impact test results in terms of reliability function or probability of failure.

2. Research Significance

Despite the plethora of previous researches in statistical analysis of impact strength of FRC; there is only one study reporting[4] the impact strength of FRC in terms of reliability level, using the graphical method of two parameter Weibull distribution. Hence, in this study proposes a four-different novel method for the computation of Weibull parameter (Shape parameter) based on the test results of earlier researchers [5, 22-28] as shown in Table 1 and 2.The precision of the proposed four novel methods are verified with power density method and tested with three goodness of fit test. Subsequently, the impact failure strength was offered in terms of reliability level.

3. Weibull Distribution

Various literatures have adopted Weibull distribution for computing the impact strength and fatigue life of concrete, owing to its simple nature and flexibility [4, 13, 26, 28-31]. In general, the Weibull distribution is given in the form of probability density function f(N) and cumulative distribution function F(N) as given below[32, 33], based on the impact strength data.

$$f(N) = \frac{\gamma}{\alpha}\left(\frac{N}{\alpha}\right)^{\gamma-1} exp\left[-\left(\frac{N}{\alpha}\right)^{\gamma}\right] \quad (1)$$

$$F(N) = 1 - exp\left[-\left(\frac{N}{\alpha}\right)^{\gamma}\right] \quad (2)$$

where γ and α denotes the Weibull parameters and N represents the impact strength.

Table 1: Experimental drop weight hammer test results of earlier researcher result.

S. No	Nataraja et al., (1999)	Song et al., (2005-a)	Badr et al., (2005)		Song et al., (2005-b)		Yu et al., (2011)	
	Batch 1	HSFRC	Batch 1	Batch 2	SPHFRC	SFRC	SFRC20	SFRC35
1	270	1650	73	129	290	425	62	258
2	140	1590	30	81	400	352	99	278
3	95	2088	65	25	220	196	167	368
4	80	3590	18	28	320	750	197	418
5	86	1525	121	134	301	156	278	512
6	181	1238	95	43	711	320	455	608
7	189	1336	135	79	261	436	-	-
8	210	2718	40	141	244	250	-	-
9	60	1385	127	73	228	494	-	-
10	70	2832	100	89	467	344	-	-
11	128	1424	38	52	210	293	-	-
12	153	1780	141	85	727	243	-	-
13	131	2074	89	103	308	530	-	-
14	222	1617	121	20	360	140	-	-
15	68	1490	60	98	276	293	-	-
16	-	1478	27	101	446	270	-	-
17	-	1580	173	74	410	366	-	-
18	-	1224	41	16	350	420	-	-
19	-	1316	104	63	409	300	-	-
20	-	1449	89	95	384	228	-	-
21	-	2967	-	-	256	252	-	-
22	-	2108	-	-	427	240	-	-
23	-	1386	-	-	385	215	-	-
24	-	1871	-	-	399	538	-	-
25	-	1407	-	-	700	243	-	-
26	-	1897	-	-	846	383	-	-
27	-	1987	-	-	319	317	-	-
28	-	2433	-	-	300	265	-	-
29	-	1501	-	-	452	290	-	-
30	-	1292	-	-	390	186	-	-
31	-	3900	-	-	333	370	-	-
32	-	5609	-	-	256	165	-	-
33	-	1223	-	-	207	302	-	-
34	-	2535	-	-	358	318	-	-
35	-	1763	-	-	200	193	-	-
36	-	1600	-	-	198	247	-	-

37	-	1874	-	-	300	326	-	-
38	-	1370	-	-	336	590	-	-
39	-	2150	-	-	525	246	-	-
40	-	1429	-	-	250	450	-	-
41	-	1900	-	-	270	351	-	-
42	-	1456	-	-	124	181	-	-
43	-	1274	-	-	208	1150	-	-
44	-	1775	-	-	356	295	-	-
45	-	1741	-	-	331	180	-	-
46	-	1561	-	-	437	256	-	-
47	-	1993	-	-	320	320	-	-
48	-	1606	-	-	295	170	-	-
Mean	139	1896	84	76	247	234	210	407
SD	64	802	43.9	37.3	133	138	142	136

Table 2 : Experimental drop weight hammer test results of previous researcher result.

S. No	Rahmani et al., (2012)			Mastali et al., (2016)			Ding et al., (2017)			
	CFRC	PFRC	SFRC	CFRP-0.25	CFRP-0.75	CFRP-1.25	PP4	PP6	SF20	SF35
1	153	49	390	30	110	151	22	35	31	25
2	75	42	157	61	66	97	32	39	29	38
3	133	85	168	44	82	132	30	34	49	54
4	176	44	281	59	39	83	35	44	36	57
5	46	39	383	29	75	40	39	41	67	59
6	268	84	346	66	62	121	42	46	99	97
7	200	40	391	47	104	124	-	-	-	-
8	120	35	192	90	58	165	-	-	-	-
9	64	104	251	90	57	45	-	-	-	-
10	171	29	308	47	69	109	-	-	-	-
11	118	50	365	52	106	73	-	-	-	-
12	27	34	176	49	78	94	-	-	-	-
13	105	89	135	42	48	107	-	-	-	-
14	24	167	166	29	109	51	-	-	-	-
15	82	45	198	70	54	96	-	-	-	-
16	119	139	124	34	68	144	-	-	-	-
17	138	43	240	39	40	94	-	-	-	-
18	103	32	135	31	85	187	-	-	-	-
19	129	127	111	67	52	66	-	-	-	-
20	114	57	154	49	159	136	-	-	-	-
21	153	105	102	63	133	86	-	-	-	-
22	82	70	170	64	119	183	-	-	-	-
23	141	101	251	19	25	135	-	-	-	-
24	98	94	307	45	64	71	-	-	-	-
25	164	50	361	87	33	34	-	-	-	-
26	139	88	192	34	61	168	-	-	-	-
27	99	126	177	93	71	125	-	-	-	-
28	75	27	302	42	87	59	-	-	-	-
29	30	43	139	76	83	70	-	-	-	-
30	180	70	173	50	64	174	-	-	-	-
31	144	63	214	40	126	129	-	-	-	-
32	115	98	252	37	114	48	-	-	-	-
33	-	-	-	52	86	99	-	-	-	-
34	-	-	-	58	62	141	-	-	-	-
35	-	-	-	45	49	73	-	-	-	-
36	-	-	-	34	96	101	-	-	-	-
37	-	-	-	56	66	83	-	-	-	-
38	-	-	-	51	59	83	-	-	-	-
39	-	-	-	32	54	76	-	-	-	-
40	-	-	-	49	87	94	-	-	-	-
Mean	118	71	228	51.29	76.49	103.71	33	40	52	55
SD	53	36	90	18.29	29.1	40.66	7	5	27	24

Several methods have been suggested by different researchers in literature to determine these Weibull parameters, which include Justus Empirical Method (EM), Moment Method (JMM), Maximum Likelihood Method (MLM), Modified Maximum Likelihood Method (MMLH), Method of Moments (MM), Least Squares (LS), Graphic Method (GM), Power Density Method (PDM), Energy Pattern Factor Method (EPFM), Equivalent Energy Method(EEM) Justus Moment Method(JMM) etc [34-40].

The chi-square, moments and regression methods were compared byDorvlo [41] for determining Weibull parameters and it was found that the chi-square method performed well over the other two methods. A novel method called energy pattern factor method was established by Akdag and Dinler [42] to assess the Weibull parameters and it was compared with GM and MLM using the wind data obtained from different locations in Turkey. The proposed novel method was found to be appropriate for comparing the mean wind speed and wind power.
The MLM, MMLM, GM and PD methods used for determining the Weibull parameters were compared by Saleh et al. [43], based on the goodness of fit test and it was found that MLM was more suitable. A comparison was made between the EM and EPFM by Mohammadi and Mostafaeipour [44], to verify their accuracy in analysing wind power in Zarrineh, Iran. Based upon the hourly, monthly, seasonal and yearly analysis, the PDM was recognized as more proper method. Six different methods that are used for computing the Weibull parameters for denoting the distribution of wind speed in Garoua, Nigeria, were compared by Kidmo et al. [45] and the results revealed that the EPFM was more appropriate over other methods, while the GM was poor in estimating the wind speed distribution.Azad et al. [46] made the comparison of seven methods (GM, PDM, EEM, MLM, MM, MMLM and JMM) to determine the Weibull parameters and found the best method using six GOF tests It was revealed that MM is the best method and followed by MLM and PDM. Based on the literature there is not a single unique method that fits to all the applications. Some methods are efficient over the others. Due to the lack of a specific method for estimating Weibull parameters accurately for all kind of applications, the present study involves the development of four novel methods that evaluates the Weibull parameters accurately.

3.1 Power Density Method (PDM)

Initially, the EPF is calculated to determine the shape and scale factor. Power density method (PDM) was established by Akdag and Dinler owing to the differences in EPF, ranging from 1.45 to 4.4 [42]. Results suggested that the accuracy of PDM approximation is greatest for the shape parameter value ranging from 1.2 to 2.75 [39]. The shape and scale parameter of Weibull distribution is obtained from the following equation, in which r(.) is the Gamma function.

$$\gamma = 1 + \frac{3.69}{(Epf)^2} \quad (3)$$

$$\alpha = \frac{\bar{N}}{r(1+\frac{1}{\gamma})} \quad (4)$$

3.2 A Four Novel Energy Pattern Factor Method (NEPFM)

Impact strength and its distribution are the important elements that plays a vital role in designing concrete structures under impact loading. The ratio between average of cubic impact strength values and the cube of average impact strength values denotes the EPF which is expressed by Eq. (5).

$$EPF = \frac{\overline{N^3}}{\bar{N}^3} \quad (5)$$

where $\overline{N^3}$ is average of cubic impact strength values and $\bar{N}^3$is the cube of average impact strength values.By considering the Weibull distribution moments, EPF is given by Eq. (6) as follows,

$$EPF = \frac{\int_0^\infty N^3 f(N)dn}{(\int_0^\infty N f(N)dn)^3} \quad (6)$$

On simplification, the Eq. (6) is transformed to Eq. (7) which represent the EPF.

$$EPF = \frac{r(1+\frac{3}{\gamma})}{r^3(1+\frac{1}{\gamma})} \quad (7)$$

The variation of EPF for impact failure strength is illustrated in Fig. 1, and this variation ranges from 1.02 to 6.07. Also, the variation of shape parameter of Weibull distribution for the impact failure strength, ranges from 1.10 to 4.52. Hence, an attempt has been made in this study to propose a four-novelmethod of approximation with larger accuracy involving the shape parameter ranging from 1.10 to 4.52. For this purpose, an expression has been modelled using Rational Polynomial Model (RPM), Weibull Model (WMM)and Reciprocal Quadratic Model (RQM) as given in Eq. (8)-(10) and it is termed as Novel Energy Pattern Factor Method (NEPFM), which is unique and suitable for estimating parameter in numerous applications. Thus, the shape parameter involving the EPF value is given by Eq (8)-(10).

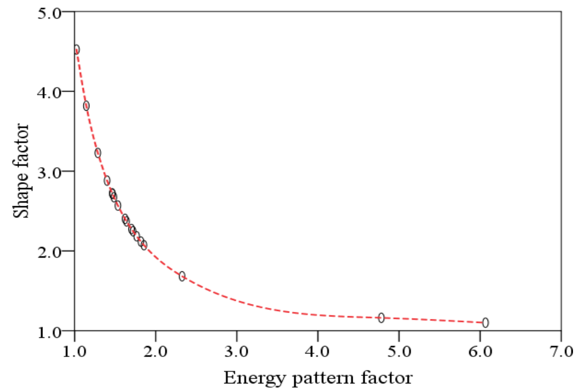


Fig. 1: EPF variations for shape factor between 1.02 to 6.07.

3.2.1 Rational Polynomial Model (RPM)

Rational method is described in terms of the degree of the numerator/the degree of the denominator. Like polynomials, rational method is often used when a simple empirical model is required and flexibility with data that has a complicated structure [39]. Rational quartic polynomials model is expressed by the Eq (8).

$$y = \left[\frac{A+Bx+Cx^2+Dx^3+Ex^4}{F+Gx+Hx^2+Ix^3+x^4}\right] \quad (8)$$

3.2.2 Weibull model Method

Weibull curve can be represented by the use nonlinear least squares to fit the curve is expressed as.

$$y = A - Be^{-Cx^D} \quad (9)$$

3.3.3 Reciprocal Quadratic

If impact strength data inclines down to a floor, or rises to a ceiling as the input increases (e.g., approaches an asymptote), can fit this type of curve in reciprocal linear regression (1/X).

$$y = 1/(A + Bx + Cx^2) \quad (10)$$

Table 3: Coefficients of scale parameter from NEPFM

Coefficients	RPM	WMM	RQM
A	187.259	43.734935	-0.182564
B	-31.0295	42.72441	0.439009
C	62.1261	0.089846	-0.043537
D	-15.2525	-2.063732	-
E	0.857728	-	-
F	7.8087	-	-
G	-23.2708	-	-
H	75.7671	-	-
I	-17.7883	-	-

Table 4: Computer shape parameters from PDM and NEPFM.

Methods	Nataraja et al., (1999)	Song et al., (2005-a)	Badr et al., (2005)		Song et al., (2005-b)		Yu et al., (2011)	
	Batch 1	HSFRC	Batch 1	Batch 2	SPHFRC	SFRC	SFRC20	SFRC35
PDM	2.37	2.25	2.12	2.28	1.16	1.10	1.68	3.23
RPM	2.37	2.25	2.12	2.28	1.16	1.10	1.68	3.23
WMM	2.37	2.25	2.11	2.27	1.16	1.10	1.68	3.23
RQM	2.38	2.25	2.12	2.28	1.09	1.14	1.66	3.22
Average	2.37	2.25	2.12	2.28	1.14	1.11	1.67	3.23

Table 5: Computer shape parameters from PDM and NEPFM.

Methods	Rahmaniet al., (2012)			Mastali et al., (2016)			Ding et al., (2017)			
	CFRC	PFRC	SFRC	CFRP-0.25	CFRP-0.75	CFRP-1.25	PP4	PP6	SF20	SF35
PDM	2.40	2.07	2.67	2.88	2.72	2.71	3.82	4.52	2.18	2.57
RPM	2.40	2.07	2.67	2.88	2.72	2.71	3.82	4.52	2.18	2.57
WMM	2.40	2.07	2.67	2.88	2.72	2.72	3.82	4.52	2.18	2.57
RQM	2.41	1.94	2.68	2.88	2.73	2.72	3.81	4.52	2.19	2.57
Average	2.40	2.03	2.67	2.87	2.72	2.72	3.82	4.52	2.18	2.57

3.3 Goodness of Fit Test

The performance of proposed method is commonly analysed using the goodness of fit test and hence, in this study two goodness of fit tests namely Root Mean Square Error (RMSE), Relative Percentage of Error (RPE) and Mean Bias Error (MBE) wereutilized as.

(a) Root mean square error (RMSE)

The deviations between the experimental and computed values are obtained by RMSE, if RMSE value close to zero which indicates the higher accuracy [47], and it is described as:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(N_m - N_c\right]^{1/2} \quad (11)$$

(b) Relative Percentage Error (RPE)

The RPE shows the percentage difference between the experimental value (N_m) and computed value(N_c)and its difference varies between +10% and -10% are generallyreasonable[48], RPE can beexpressed as:

$$RPE = \left(\frac{N_c - N_m}{N_m}\right) x100\% \quad (12)$$

(c) Mean Bias Error (MBE)

MBE are a measure of difference between the experimental and computed value [47].

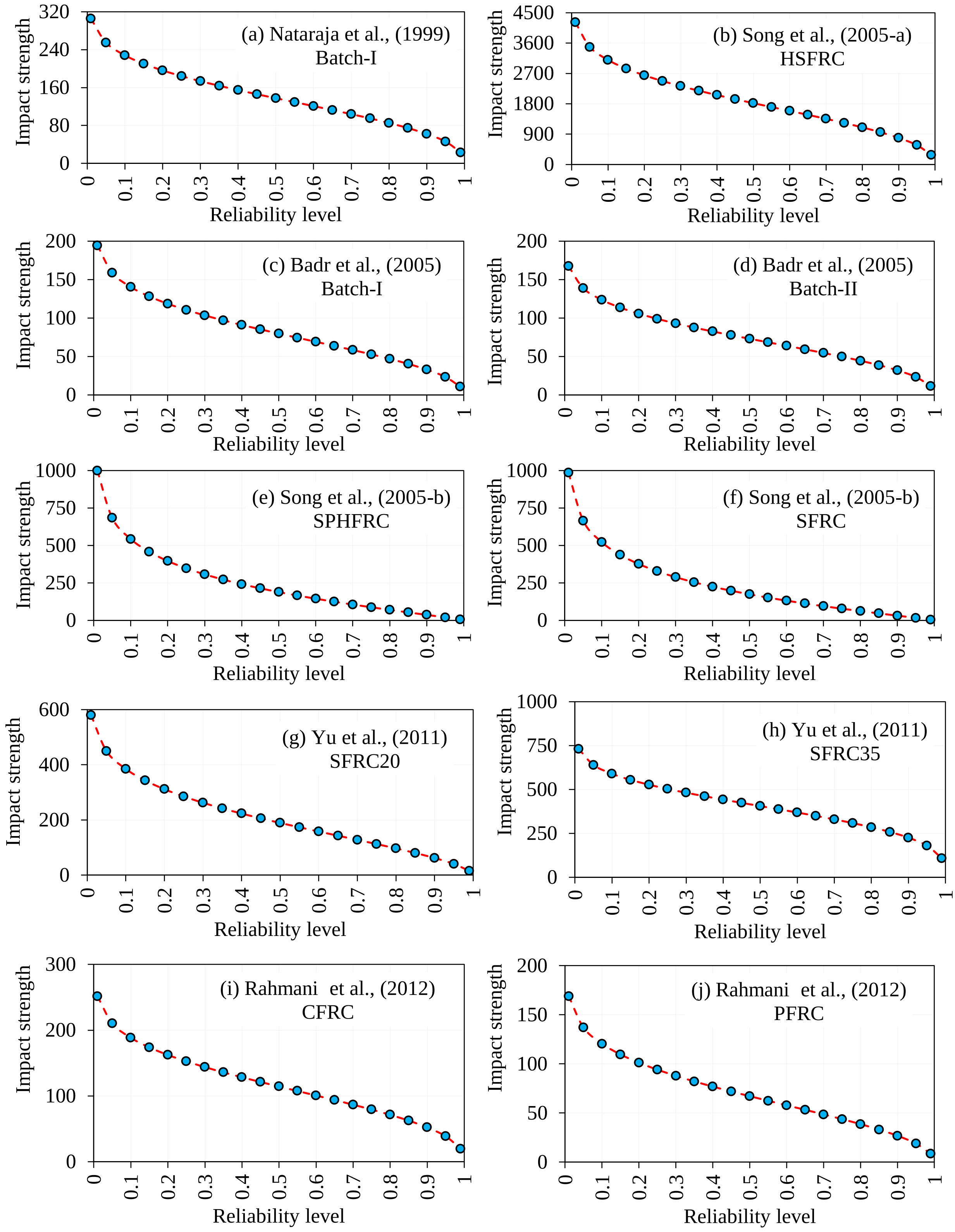
$$MBE = (N_m - N_c) \quad (13)$$

Table 6: Statistical test efficiency

Authors	Mix Id	RMSE	RPE	MBE
Nataraja et al., (1999)	Batch 1	0.000	0.090	-0.002
Song et al., (2005-a)	HSFRC	0.000	0.070	-0.002
Badr et al., (2005)	Batch 1	0.000	0.022	0.000
	Batch 2	0.000	0.076	-0.002
Song et al., (2005-b)	SPHFRC	0.158	-2.163	0.025
	SFRC	0.000	1.248	-0.014
Yu et al., (2011)	SFRC20	0.096	-0.548	0.009
	SFRC35	0.026	-0.020	0.001
Rahmani et al., (2012)	CFRC	0.000	0.092	-0.002
	PFRC	0.209	-2.117	0.044
	SFRC	0.000	0.077	-0.002
Mastali et al., (2016)	CFRP-0.25	0.000	0.043	-0.001
	CFRP-0.75	0.000	0.070	-0.002
	CFRP-1.25	0.000	0.071	-0.002
Ding et al., (2017)	PP4	0.059	-0.091	0.003
	PP6	0.052	-0.059	0.003
	SF20	0.000	0.051	-0.001
	SF35	0.000	0.088	-0.002

The value of shape parameter for an impact failure strength corresponding to earlier researchers results, computed using the PDM and three NEPFM are exhibited in Table4 and 5.The average results of computed shape parameters were used for comparison and reliability analysis. It can be noticed that the deviation between these three NEPFMare very small and gives very close results as compared with the PDM. The goodness of fit tests RPE, RMSE and MBE gives the values nearer to zero as shown in Table 6, which indicates that the proposed three NEPFM are acceptable and highly sufficient for computing the shape parameters exactly. The uniqueness of this proposed NEPFM is that, it does not involve intricate iterative process or solving problem by linear least square method. Hence, the Weibull shape parameters can be assessed accurately if the average impact failure strength value and EPF value are available. By using Weibull parameters, the impact failure strength in terms of reliability (N_R) can be computed using Eq (12) [4,13, 48-50] as given below.

$$N_R = \alpha(-\ln(R)^{\frac{1}{\gamma}}) \quad (12)$$


(a) Nataraja et al., (1999)
Batch-I
Impact strength
320
240
160
80
0
Reliability level
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
(b) Song et al., (2005-a)
HSFRC
Impact strength
4500
3600
2700
1800
900
0
Reliability level
(c) Badr et al., (2005)
Batch-I
Impact strength
200
150
100
50
0
Reliability level
(d) Badr et al., (2005)
Batch-II
Impact strength
200
150
100
50
0
Reliability level
(e) Song et al., (2005-b)
SPHFRC
Impact strength
1000
750
500
250
0
Reliability level
(f) Song et al., (2005-b)
SFRC
Impact strength
1000
750
500
250
0
Reliability level
(g) Yu et al., (2011)
SFRC20
Impact strength
600
400
200
0
Reliability level
(h) Yu et al., (2011)
SFRC35
Impact strength
1000
750
500
250
0
Reliability level
(i) Rahmani et al., (2012)
CFRC
Impact strength
300
200
100
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Reliability level
(j) Rahmani et al., (2012)
PFRC
Impact strength
200
150
100
50
0
Reliability level

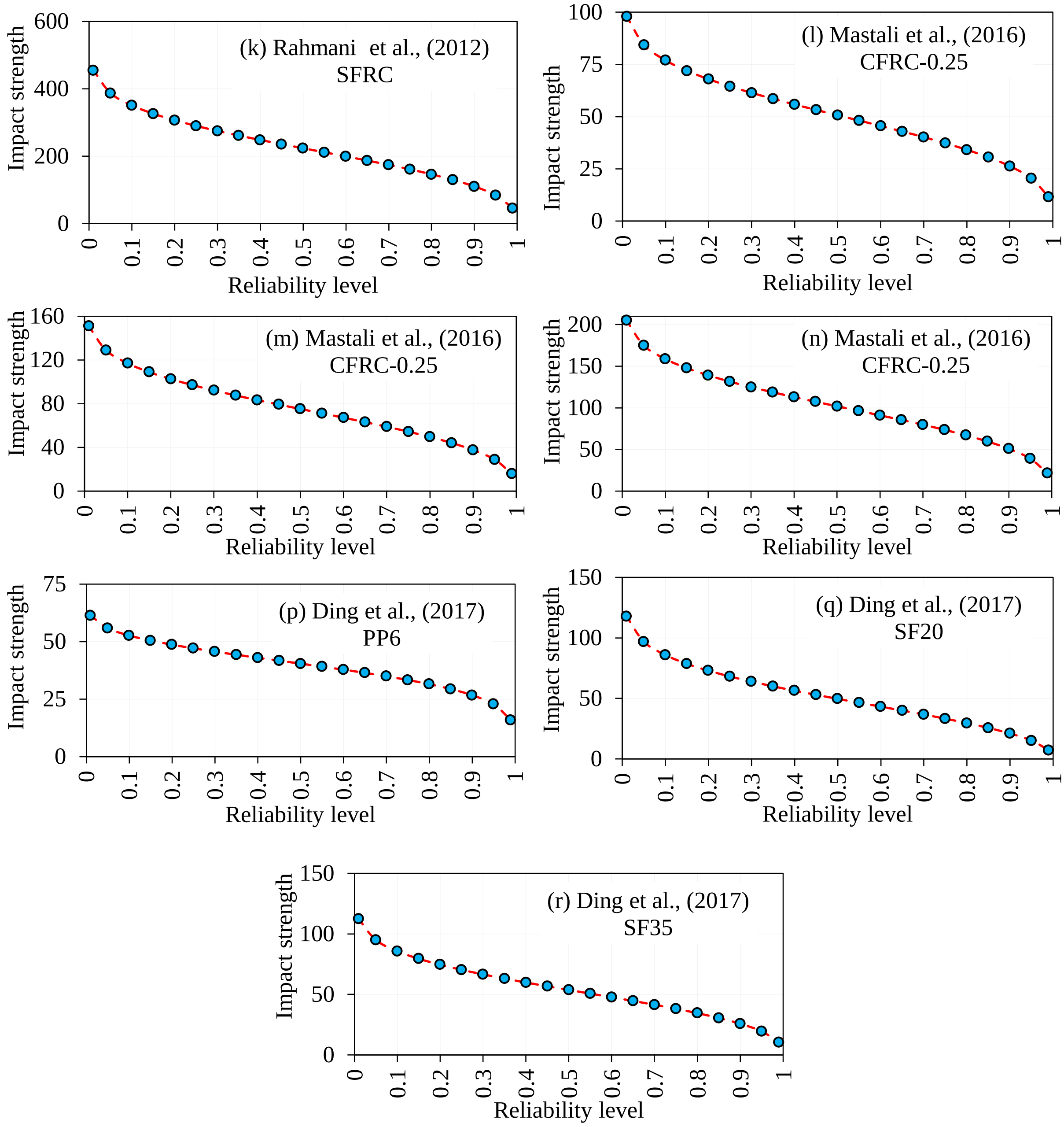

Fig. 2: (a)-(r) Weibull reliability curves

Figs. 2 (a)-(r) illustrates the impact failure strength in terms of reliability is calculated by using Eq. (12) with the average of shape parameter obtained from three NEPFM and PDM. The Weibull reliability curve of Nataraja et al., (1999) shown in Fig. 2 (a) demonstrates the impact failure strength values is roughly less than or equal to 23 (Number of blows causes failure). For more certain assessment, consider 0.90 reliability level from Fig. 2 (a) and when this value is substituted in Eq. (12) and solved, the impact failure strength was 62. On the other end, considering the 0.1 reliability level the impact failure strength values 228. Likewise, the impact strength obtained from the Weibull reliability curve of Song et al., (2005-a) as shown in Fig 2 (b). From Fig 2, the impact failure strength at 0.9 and 0.1 reliability level were 788 and 3099 respectively can be obtained. In the same way, the impacts failure strength could be obtained from the Fig 2 (c) to (r) at required reliability level. The two parameter Weibull distribution discards the practice of taking average of test results. In this view, Weibull distribution enables the design engineers to choose the impact failure strength for the design calculation in terms of required level of reliability.

4. Conclusions

The drop hammer experimental test results are imprecise owing to lack of its reliability. Based on the proposed four different novel methods, the following conclusions are arrived:
In this study, a four NEPFM were proposed to compute the Weibull shape parameter for impact failure strength applications. By using earlier researcher's experimental results, the values of shape factor were computed using proposed NEPFM and their performance were compared with PDM and three goodness of fit tests.It can be concluded that the computed shape parameters in four NEPFM are almost same and showed that the less deviations as compared to PDM method. Moreover, four NEPFM had a RMSE, MBE and RPE values close to zero which indicates the high degree of goodness of fittest. Therefore, the proposed NEPFM is very suitable and efficient to compute the shape parameter for the impact failure strength applications. Besides that, the NEPFM eliminates intricate iterative process involved in conventional methods as it comprises easier calculations. This

uniqueness of NEPFM makes it a better choice for computation of Weibull shape parameters in various engineering research areas.

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